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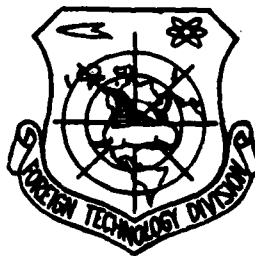
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CO₂-N₂ LASER USING THE COMBUSTION HEAT OF ACETYLENE

by

Michael Syczewski



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By: Michael Syczewski

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CO₂-N₂ LASER USING THE COMBUSTION HEAT OF ACETYLENE

Michal Syczewski
Military Technical Academy, Warsaw

The test stand of a gasodynamic laser based on the use of the products and energy of acetylene combustion is described. The results of studies are presented and theoretical parameters of the stream of gases in the area of resonance cavity are determined. It was found that acetylene can serve as a good fuel for a gasodynamic laser under the condition that sufficient cooling of the products in resonance cavity is ascertained.

Chemical energy can be utilized to obtain coherent radiation in two basic ways. In the first case, molecules in an excited oscillation state are formed as a result of elementary steps of exothermic reactions. When the reaction is sufficiently fast, the reaction products form a system of molecules with inversion of the population of oscillation levels - which is the necessary condition for obtaining the laser radiation from such a center.

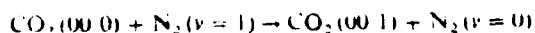
In the second case, the energy of the chemical reaction is first converted into heat, and thus the products of reaction are characterized by high temperature. At this high temperature, in the Boltzman distribution of energy levels, many molecules (e.g., CO₂ and N₂) will be found at excited oscillation levels. After rapid decompression of such gases, there will be a fast drop in their translational temperature, while the population of certain (metastable) energy levels will remain the same as the initial temperature. Because of such a freezing of certain excited states, one can obtain the inversion of population for certain pairs of levels. The lasers on active centers obtained in this way are called gasodynamic lasers. This name, however, is very broad. This group of lasers includes also lasers in which gases are heated by electric arc, shock wave, etc. The type of laser described here derives its energy from a chemical reaction; hence it is a special type of gasodynamic

laser.

As in the majority of molecular lasers, the working gas of this type of lasers is a gas mixture whose principal components are CO_2 and N_2 . Nitrogen in this case is not an inert gas, but it serves the role of a reservoir of oscillation energy to supply the upper laser of CO_2 molecules. The diagram of oscillation levels of CO_2 and N_2 molecules is presented in Figure 1.

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The first excited oscillation level of N_2 is nearly the same as the level (00^01) of CO_2 molecule. Because of this fact, fast migration of energy from excited molecules of nitrogen to CO_2 molecules is assured:



The return of CO_2 molecules to the ground level may take place through intermediate levels either in a radiationless way (wavy arrows) or with radiation of energy quanta; the broadened straight arrow shows the working laser transition.

In gasodynamic lasers which utilize the heat of combustion of hydrocarbons, we use such a system of substrates as to obtain products with the optimum $\text{CO}_2 : \text{N}_2 : \text{H}_2\text{O}$ ratio [1/]. The presence of H_2O molecules accelerates the emptying of $\text{CO}_2(01^10)$ and (10^00) levels, thereby increasing the degree of inversion of populations at the $\text{CO}_2(00^01)$ and (10^00) levels. However, the content of water higher than 2% causes also the radiationless relaxation from the working $\text{CO}_2(00^01)$ level. Hence, the first lasers of this type were based on the reaction of the combustion of gases not containing hydrogen ($\text{CO}, \text{C}_2\text{N}_2$) [1/, 2/, 3/]. Later studies have shown, however, that the harmful effect of large quantities of water can be reduced by changing conditions of gasodynamics of the stream of working gases [1/, 4/, 6/]. In many studies of this type, the active centers were in-

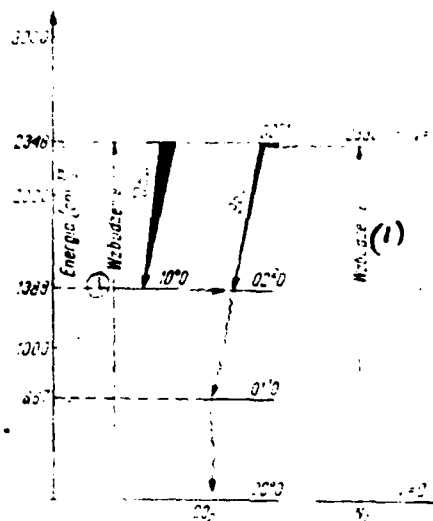


Figure 1. Diagram of oscillation levels of CO_2 and N_2 molecules

1 - Excitation

investigated only as centers enhancing the radiation of CO_2 laser with continuous action. In our case, we utilized the reaction of the combustion of acetylene which gives products with contents of water larger than the optimal one, and these products were used as a center generating coherent radiation.

Experimental Conditions

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The diagram of the test stand of the laser is presented in Figure 2. The combustion chamber 1 (capacity ~ 30 l) was filled with a mixture of acetylene with appropriate amounts of oxygen and nitrogen. Then the process of combustion was initiated by means of a spark plug 5. As a result, the pressure in

the chamber increases to a predetermined value. At a certain pressure, the pressure-type contact on the electromagnetic clutch (not shown in the Figure) is switched off. This clutch supports the closing valve (flap) 2. Under the action of pressure, this valve opens and the products of combustion pass to the vacuum tank 4 through a shallow nozzle 3. The width of the nozzle (the length of the active center) is 20 cm; the applied critical cross-section, 0.07 x 20 cm; the angle of opening of the supersonic part, starting from the critical gap, is 60°- and then the surface is profiled gently, becoming a parallel-walled canal (the height of the canal 2.2 cm). Transition from a profiled cross-section to a parallel-walled canal takes place at a distance of 3.5 cm from the critical cross-section. At this distance, the axis of resonance cavity 8 passes across the canal (along its side wall). The diameter of the cavity (aperture of the laser) is 2.2 cm. The resonator is formed by mirrors: one with 100% reflection and curvature radius of 1.04 m, and the other semitransparent, multiplated (three flat-parallel 3- plates), with about 7% transmission.

Because of an imperfect action of the system of the electromagnetic clutch, part of the experiments was performed with the use of a thin polyethylene foil placed in the A - A cross-section (instead of the valve). The discussed example of generation is taken from a series of experiments carried out using the foil. As a result of burning the gas mixture and the growth of pressure, at some moment the foil becomes broken and the products fly into the vacuum tank, in analogous way as with the opening of the valve (flap). Changes of pressure in the chamber were registered by means of a loop oscillograph with the use of a tensometric sensor. The laser impulse was also registered by means of the loop oscillograph with the use of a semiconductor detector of radiation and an especially constructed amplifier. Diagram of the measuring system is shown in Figure 3.

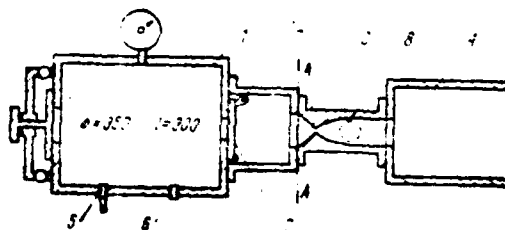


Figure 2. Diagram of a gasdynamic laser utilizing the products and energy of combustion of hydrocarbons. 1 - combustion chamber; 2 - valve; 3 - nozzle; 4 - vacuum tank; 5 - spark plug; 6 - tensometric sensor; 7 - axis of electromagnetic clutch; 8 - cross section of resonance cavity of laser.

Gases provided for combustion were in the following approximate molar ratios: $C_2H_2:O_2:N_2 = 1 : 3.25 : 14.0$. The probable composition of combustion products and the expected maximum pressure in the combustion chamber, at the assumed 588 initial conditions, were based on theoretical calculations [5]. Verification of assumptions and results of calculations were made by measuring changes of pressure in the combustion chamber.

Results and Their Interpretation

Figure 4a shows the course of pressure and power of the laser impulse for the above given composition of substrates.

An initial increase of pressure in the closed chamber occurs as a result of combustion up to the bend in the p curve (an arrow). At this moment, the flow is opened to the vacuum tank. The further shape of the curve is the resultant of two processes: continued course of chemical reaction (causing

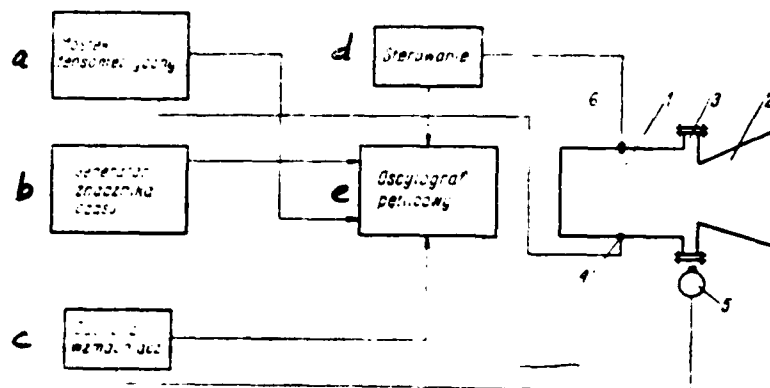


Figure 3. Block diagram of a system for measuring parameters of the laser. 1 - combustion chamber; 2 - vacuum tank; 3 - resonance cavity; 4 - tensometric sensor; 5 - detector of radiation; d - spark plug a.- tensometric bridge; b - generator of the time marker; c - amplifier; d - control; e - loop oscillograph

increase of pressure) and outflow of gases from reaction chamber to the vacuum tank (causing drop of pressure). At p_{\max} the effect of both factors is compensated. A clear drop of pressure (total completion of the reaction) is observed after about 0.15 sec from the moment of ignition of the mixture - this drop of pressure is caused only by the outflow of gases.

In the first period of the outflow of gases, when the passage to the vacuum tank is already open, but the process of combustion has not yet reached the state of chemical equilibrium (small concentration of CO_2), no generation of radiation is observed (in some experiments, the generation of minimal power was seen). The appearance of generation is observed after reaching full chemical equilibrium, i. e., when the pressure is limited only by the outflow of gases through the nozzle

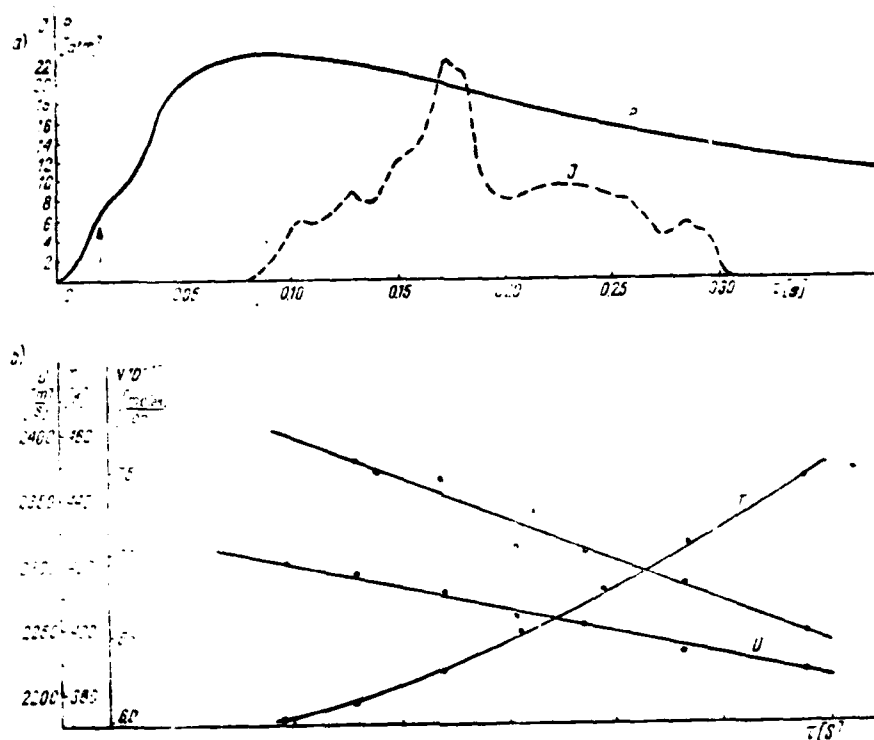


Figure 4. Change of the parameters of gases and of laser power during its operation. a.- course of pressure p in reaction chamber and radiation power I (arbitrary units); b - calculated parameters of the stream of gas in the region of resonance cavity for changing pressure in combustion chamber.

(after about 0.15 sec from the moment of ignition of the mixture). The total time of generation is about 0.2 sec. The maximum estimated power of laser radiation is about 4 W.

Termination of the generation at a pressure in combustion /589

chamber of about $11 \cdot 10^{13} \text{ N/m}^2$ evidences an incomplete utilization of the energy of the working gases. Hence it was desirable to analyze the reasons for such an early interruption of generation. For this purpose, a theoretical determination was made of a set of parameters of the stream of gas in the region of the resonance cavity (after decompression). /582

The ratio of pressure in vacuum tank p_2 to assumed pressures in the combustion chamber p_1 was calculated. It was assumed that the pressure at the outlet of the nozzle was constant and equal to $3.95 \cdot 10^3 \text{ N/m}^2$. Experiments were carried out at such a pressure in a vacuum tank, and the large volume of the tank ensured in practice the constancy of this pressure during one cycle of combustion. An average molecular weight of the products of combustion $\mu = 29$ and the probably value $k = \frac{5}{3} = 1.35$ were taken on the basis of previously made calculations [5/]. These values are close to the characteristic values for air. Utilizing this fact, we availed ourselves of the ready tables for air, and we found the Mach number M for particular values of p_2/p_1 (on the assumption that the used nozzle fulfills optimal aerodynamic conditions for each value of p_2/p_1), and also the ratio of densities p_2/p_1 [7/]. The temperatures in the combustion chamber for particular values of pressure were also taken from the work [5/]. On the basis of these data, one can calculate the density of gases in a combustion chamber $\rho_1 = p_1 \mu / RT_1$, and then the density of gases and number of molecules per unit volume in the region of resonance cavity. The temperature of gases after decompression was also calculated on the basis of tabulated data T_2/T_1 for particular values of the drop of pressure [7/]. It is necessary to point out that the temperature calculated in this way does not take into account any reactions which could occur in the time of gas flow from the critical cross-section of the nozzle to the region of the resonance cavity (a distance of 3.5 cm). The velocity of the outflow of gases was calculated from the formula: /583

$$U = a_{\text{max}} \sqrt{1 - \left(\frac{p_2}{p_1}\right)^{1/k}}$$

where

$$u_{\max} = \sqrt{2c_p T_1}$$

c_p was calculated from the known formulas for composition of gases obtained in the work [5] and for temperature T_1 .

Because of the mentioned assumptions, the absolute values of the obtained parameters could differ from real values, but the character and magnitude of changes must certainly be close to the real ones. Figure 4b shows graphically the course of changes of some parameters of the stream of gases in the resonance cavity, on the background of pressure changes in the combustion chamber and changes in intensity (power) of laser radiation. Changes of velocity of the outflow of gases and also changes of density of molecules in the considered areas of pressure are not large and cannot be the reason for the interruption of generation. The translational temperature of gases in the considered area increases with the pressure from about 100 degrees and reaches a value of about 400°K. In reality this temperature could be higher if we considered heats of reactions which could take place in the expanding area of the nozzle.

Such a high temperature causes a shortening of the lifetime of CO_2 molecules in an excited state. For the mixture $\text{CO}_2:\text{N}_2 = 1:10$ the relation is [8].

$$\tau = 3 \cdot 10^{-8} \exp(-3.88 \cdot 10^{-3} T)$$

Moreover, the higher the temperature, the lower is the number of inversions of populations of the working levels of the laser, since the lower excited levels of CO_2 molecule are then partly occupied thermally; the lower level of the laser is unoccupied to a lesser degree.

The dependence of maximal radiation power on pressure was also examined by reducing the maximal pressure, through changes in the initial amount of gases. In this case, we also

found cessation of generation at the maximal pressure $10-11 \cdot 10^3$ N/m² in the combustion chamber.

Conclusions

The conducted studies have confirmed the fact that contents of water larger than the optimal amount are not a real obstacle to generation of laser radiation. /591

The described method of conducting experiments allows one to draw a practical conclusion with regard to future construction of this type of laser. Because of the time taken by the reaction of combustion and the time required to reach the state of chemical equilibrium, the outflow of products should take place about 0.15 sec after the initiation of the reaction. In lasers of continuous action, the construction of the combustion chamber should also ensure this time of residence of gases in the chamber (from the time of leaving the burner nozzle to the time of leaving the critical cross-section of the supersonic nozzle of laser).

In our experiments, the used proportion of initial gases provided the following approximate molar percents of products: CO₂ - about 9%; H₂O - about 4.5%; O₂ - about 3%; CO - about 1%; N₂ - 82%; and smaller amounts of NO, H₂ and others. One should consider the possibility of increasing the percent amount of CO₂ in the mixture. However, an increase of the used amount of acetylene will increase even more the calorific nature of the mixture. Under the same gasodynamic conditions, it will result in such a rise of the translational temperature in the region of the resonance cavity that obtaining the laser effect will not be possible.

Speaking in another way, acetylene is a fuel which is too calorific for the described operational conditions of the laser. We would propose two basic ways of increasing utilization of the energy contained in acetylene for conversion into radiation

energy of the laser:

- to increase the degree of decompression of the products of combustion - a higher pressure in combustion chamber, and lower pressure in the vacuum tank,

- to apply in the initial mixture an additional gas that would lower the temperature of products in the combustion chamber. Such a gas could be, for instance, CO_2 which heats up, absorbing a part of the energy evolved during the combustion of acetylene, and then can function as a working gas together with carbon dioxide produced in the combustion of acetylene. This latter method of increasing the degree of utilization of energy of the combustion of acetylene appears more economical.

Further work on optimization of the operational conditions of this type of laser is in progress, and the results will be published in the near future.

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CO₂-N₂ Laser Using the Combustion Heat of Acetylene

Summary

The test stand of a gasodynamic laser based on the use of the products and energy of acetylene combustion is described. Laser radiation of several watts power was obtained from an active region of about 60 cm³. Initial test results are given and the theoretical parameters of a stream of gases in the resonance cavity region have been determined.

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